Optical Free Space Links for Satellite-Ground Communications

Dirk Giggenbach

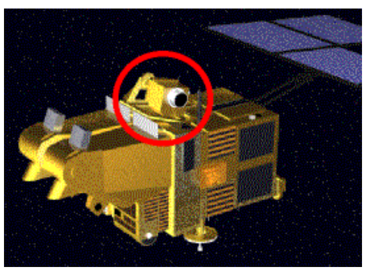
German Aerospace Center (DLR),

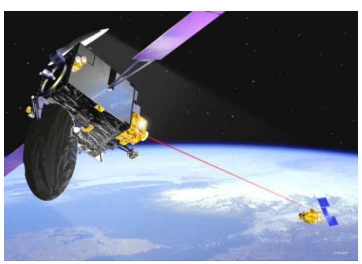
Tutorial held at **ASMS/SPSC, Livorno, 2014**

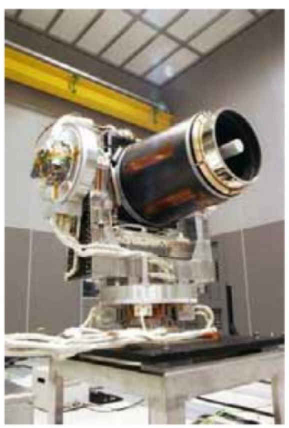
7th Advanced Satellite Multimedia Systems Conference
13th Signal Processing for Space Communications Workshop

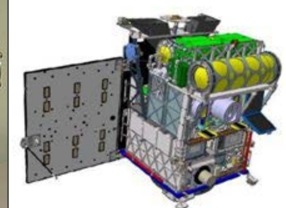
Timeline of Laser-Comm. Space-Missions (selection)

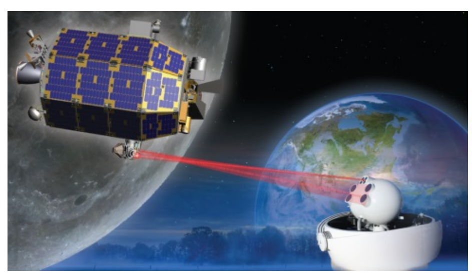
- **1994**: •ETS-VI
- **1998**: •SPOT-4
- **2001**: •Artemis → SILEX, •GEOLITE
- **2005**: •OICETS
- **2007**: •LCTSX, •NFIRE -LCTs
- **2013**: •α-Sat, •LLCD
- **2014**: •Sentinel-1A, •SOTA, •OPALS
- **2015**: •EDRS-A, •OSIRIS
- **2016**: •EDRS-C
- **2017**: •LCRD











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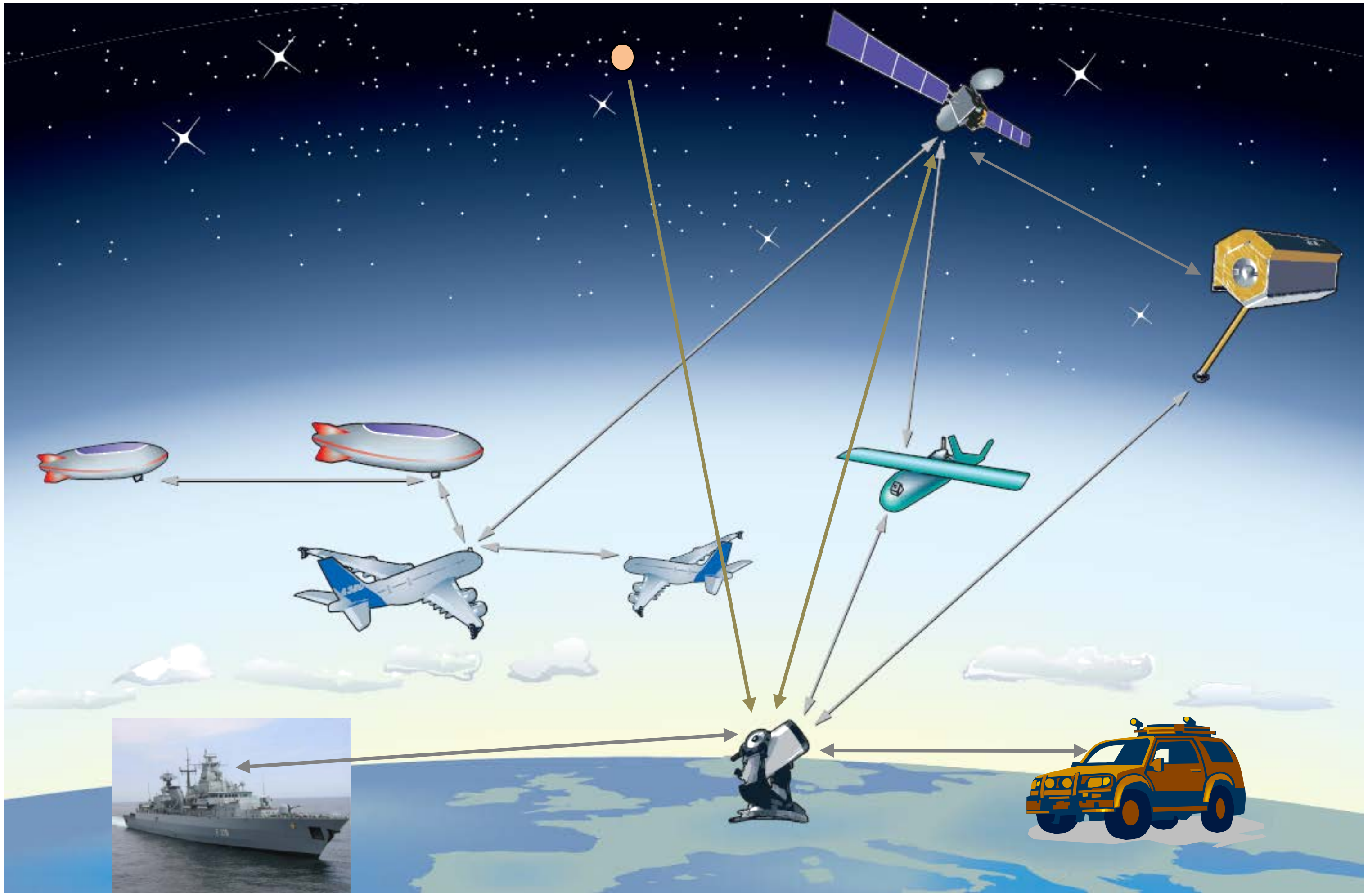
Pictures: ESA, JAXA, NICT, NASA, MIT, DLR

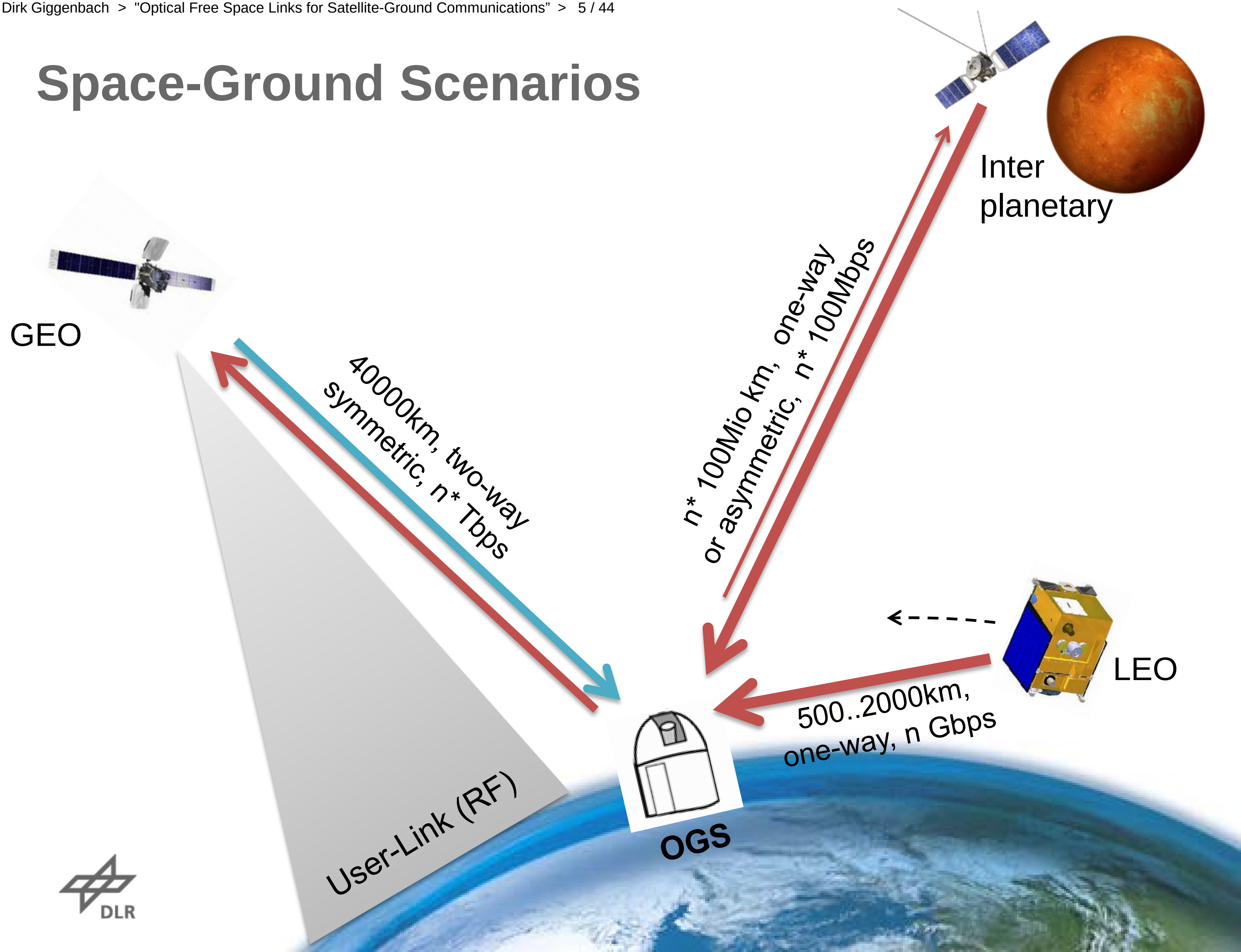
Content of this Tutorial

- Introduction to FSO in Space Applications
- Technologies and Subsystems
- Atmospheric Impact on Link Quality
- Mitigation of Atmospheric Effects
- Optical GEO Feeder-Links
- Summary

Application Scenarios of Mobile Optical Data Links



Space-Ground Scenarios



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System Sensitivity of Optical vs. RF Point-to-Point

- Diffraction limited divergence angle reduces linearly with wavelength $\rightarrow$ increase of Rx-power with $1/\lambda^2$:

$$P_{Rx} \sim \left(\frac{D_{Tx} \cdot D_{Rx}}{\lambda \cdot L} \right)^2 \cdot P_{Tx}$$

- Ideal optical receiver performance is limited by number of photons per bit, where required energy per photon increases with shorter wavelength:

$$E_{Photon} = \frac{h \cdot c}{\lambda}$$

$\rightarrow$ these two laws result in total in a *linear* increase of photon-flux density at the receiver with laser frequency

- Ideal optical systems are limited by photon-flux fluctuations, RF-systems by thermal noise:

$$\frac{SNR_{opt}}{SNR_{RF}} \sim \left(\frac{\lambda_{RF}}{\lambda_{opt}} \right)^2 \cdot \frac{2k_B T}{hc/\lambda_{opt}} \approx 4 \cdot 10^6$$

$\rightarrow$ with typical values (1µm / 1cm , T=300K) ~60dB can be achieved

Properties of Point-to-Point Laser Links

Linkbudget-Gain is invested in…

- increase of datarate
- reduction of Tx-power
- reduction of antenna (telescope) size
  → according mass-reduction

Challenges

- Link blocking by clouds and fog
  → scenario-dependent
- Signal scintillation by index-of-refraction turbulence (IRT)
- Precise pointing and tracking;
  Link acquisition

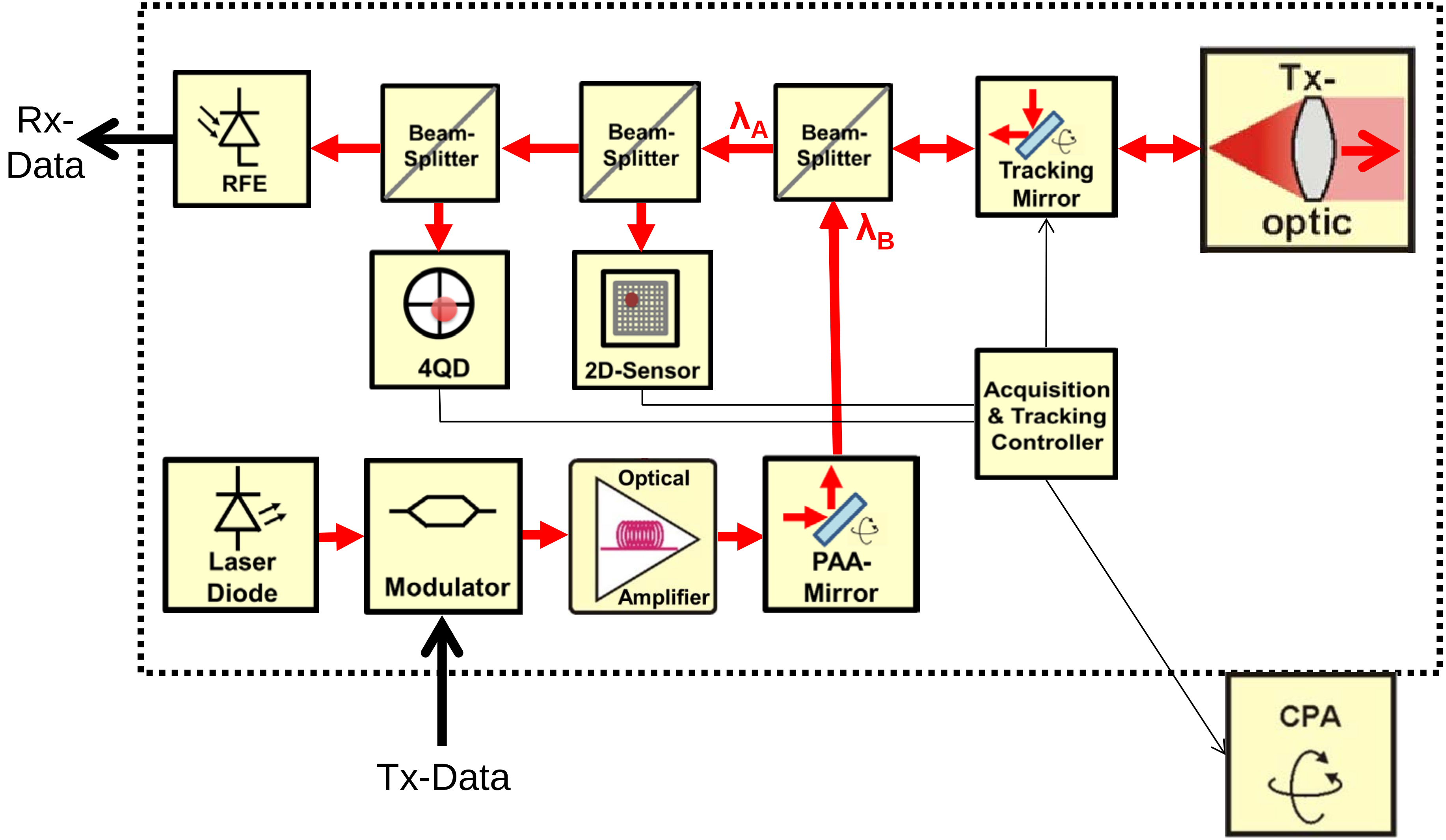
Typical parameters

- laser-wavelengths in the near infrared (850nm / 1064nm / 1550nm)
- diffraction limited Tx-divergence: below 1/1000 degree → *x* µrad
- datarates from few 100Mbps up to several Gbps are implemented

Other beneficial properties

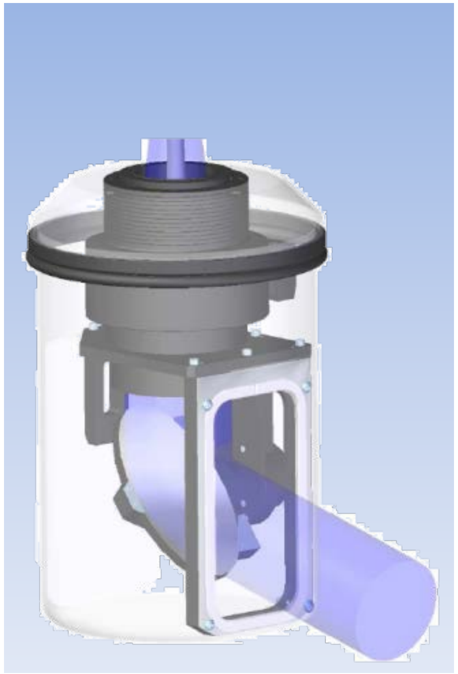
- Inherent tap proof
- No mutual interference between links
- No spectrum regulatory limitations

Components of full-duplex Space Laser Terminals

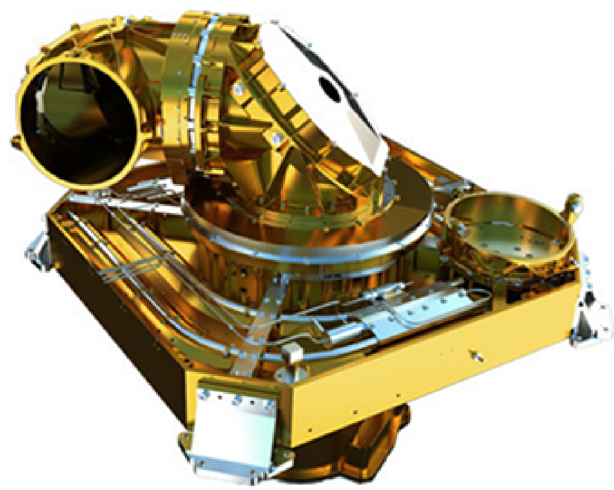


Coarse Pointing Assembly (CPA) Mechanisms

Azimuth-Elevation Gimbal (OICETS)



One-Mirror



Periscope (Alphasat)

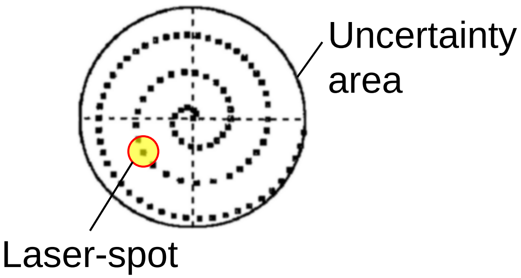
Pictures: JAXA, ESA, ViaLight

Beam-Acquisition Strategies in Space-GND Links

Orbital and Mechanical Position Uncertainties: ***~ mrad***

- OGS sends divergent Beacon towards Sat, covering uncertainty area, Sat stares with wide-FoV area-sensor in direction of OGS

- Diffraction-limited scanning towards the partner who is staring with a narrow-FoV – no extra beacon required



- Mixed methods of above, might require extra beacon, or zoom-optics, and variable FoV-Optics

FoV: Field-of-View

Modulation Formats & their Application Areas

Optical Intensity Detection (incoherent)

- Direct Detection (**IM/DD**) with On-Off Keying (OOK)
  - low to medium sensitivity
  - high data-rates
  - low implementation effort
  - → short range with atmosph. (LEO)
- **PPM** (Pulse Position Modulation)
  - sensitivity limit (photon counting)
  - high implementation effort
  - limited data-rate
  - → long-range medium-rate (Exploration)

Complex Field Detection (coherent)

- Selfhomodyne-DPSK with **PreAmp**
- **with local oscillator**: hom./heterodyne-BPSK, QAM

Both coherent options:

- high sensitivity (in Phot./bit)
- high data-rates
- requires plane Rx-wave
- atmosphere is a challenge
- → long range space links (GEO)

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Optical Ground Stations:
ESA-OGS, Izana, Tenerife, 2400m a.s.l.

- Built for SILEX (ARTEMIS)
- 1m Cassegrain-Telescope
- Coudé-Room for experimental setups

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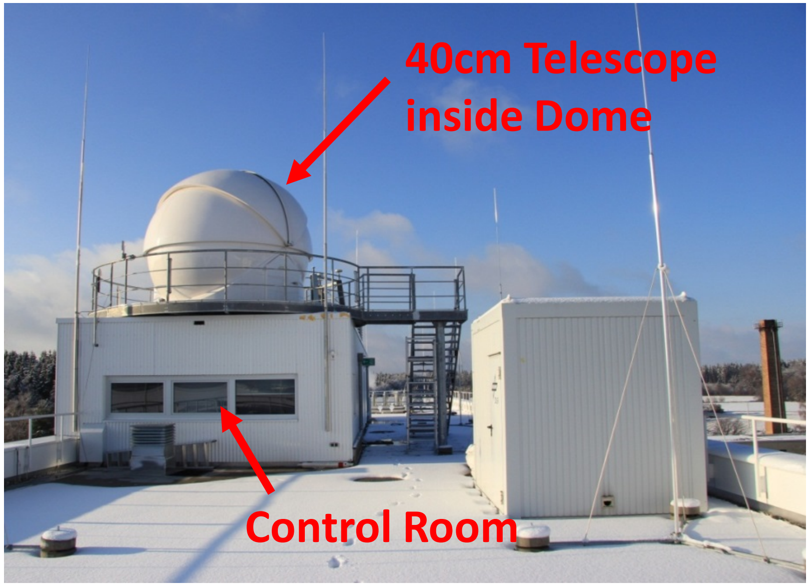
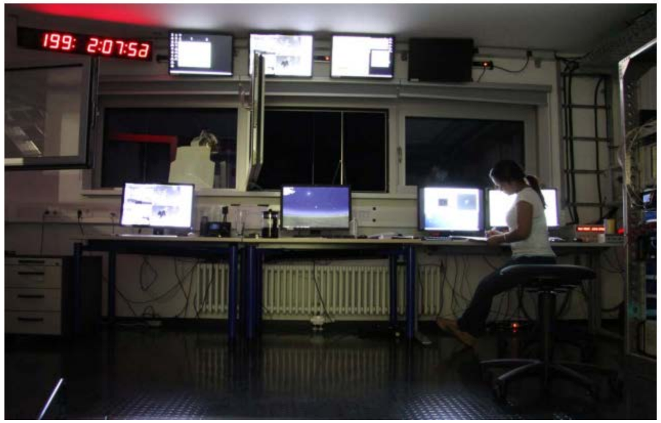
OGS-OP, DLR
(Experimental Downlinks and IRT measurement sensors)



40cm-class



Control Room of OGS-OP

More global OGSs:

- NICT (Tokyo, Kobe, …)
- JPL (Table Mountain, CA)
- NASA / MIT, for LLCD (White Sands, N.M)
- Modified SLR-stations
- …

Transportable Ground Stations

TOGS with transport van and control room

60cm-class

20cm-MOGS

Pictures by DLR, ViaLight

- Introduction to FSO in Space Applications
- Technologies and Subsystems
- **Atmospheric Impact on Link Quality**
- Mitigation of Atmospheric Effects
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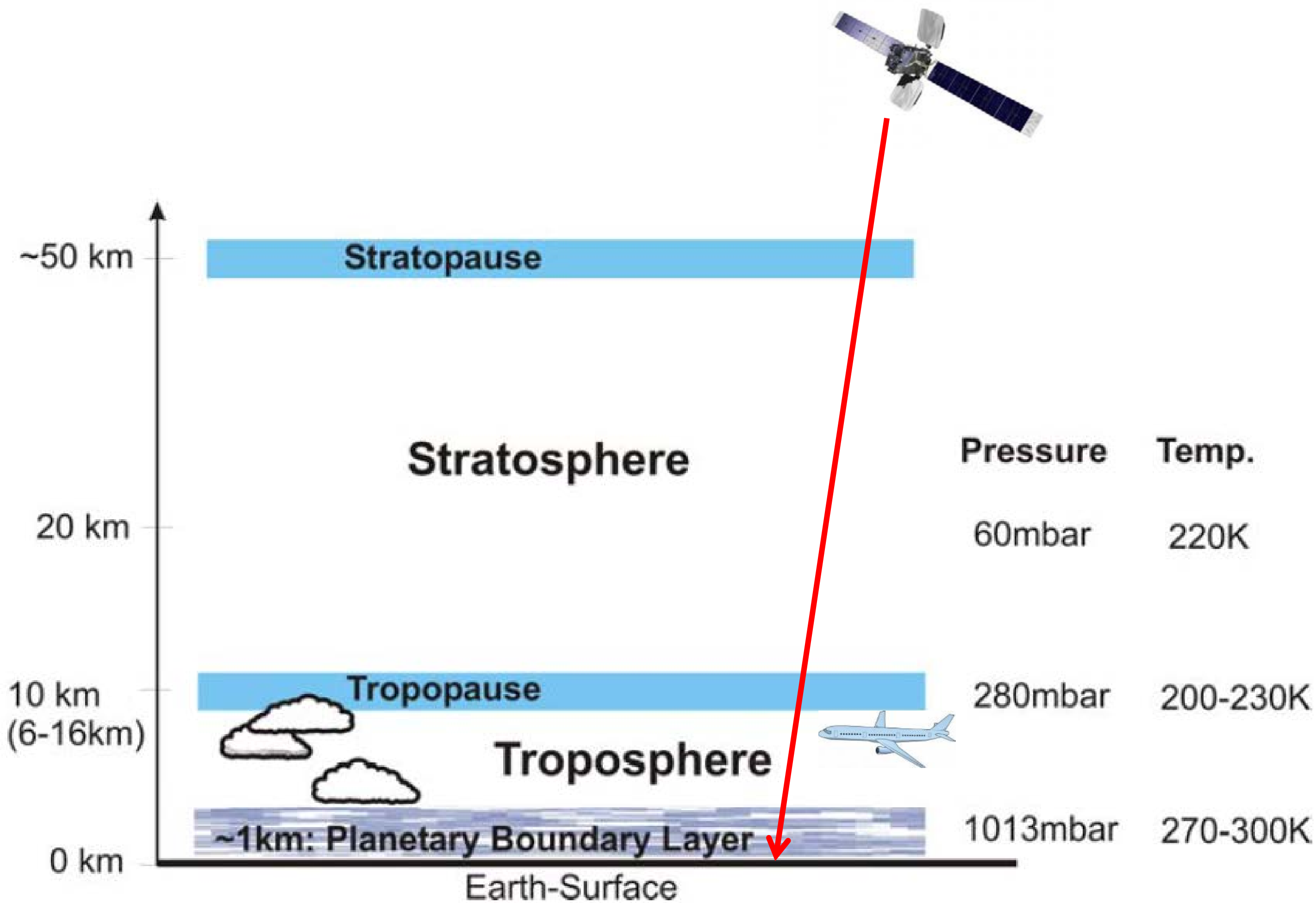
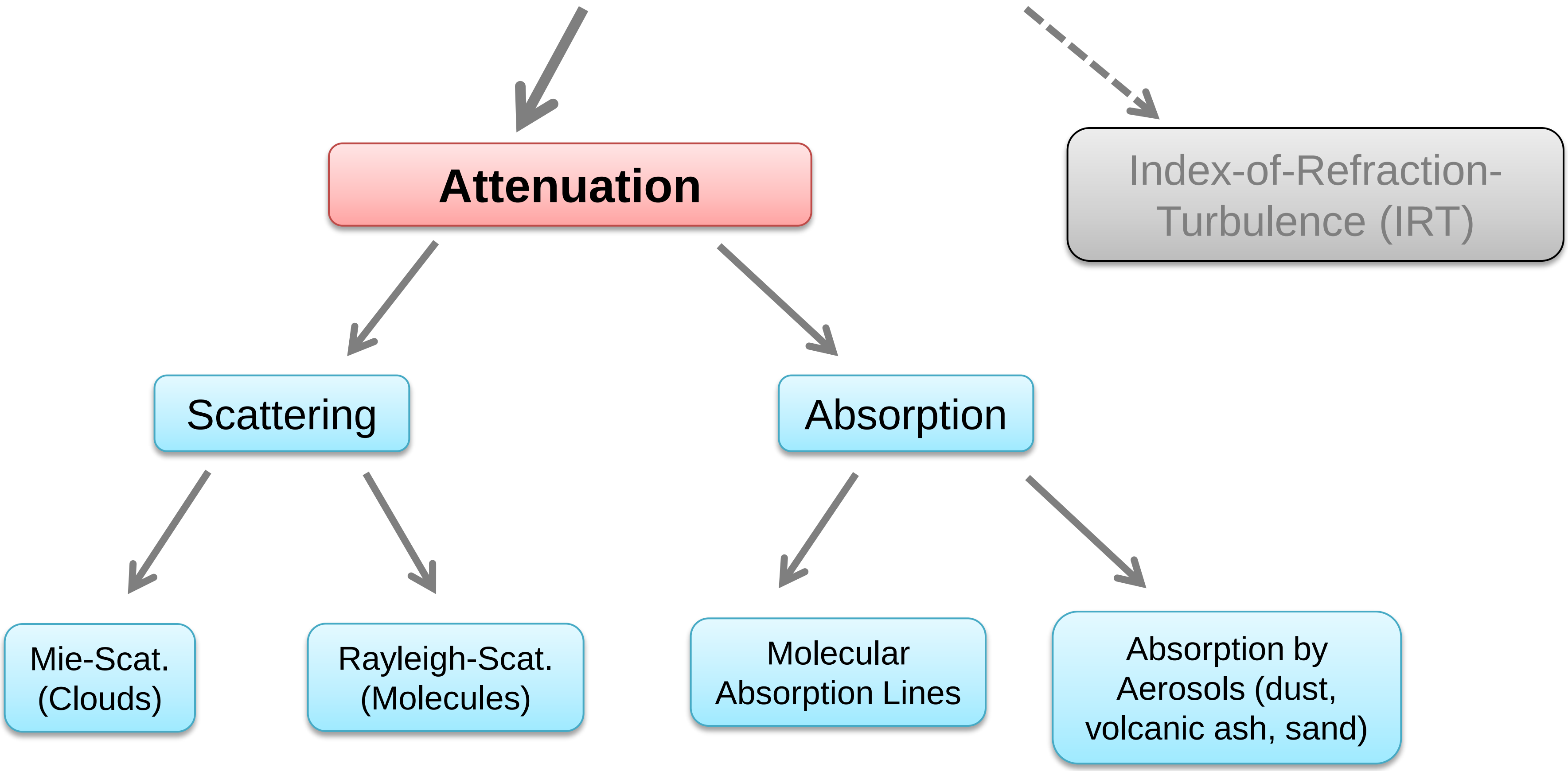
Structure of Earth‘ Atmosphere

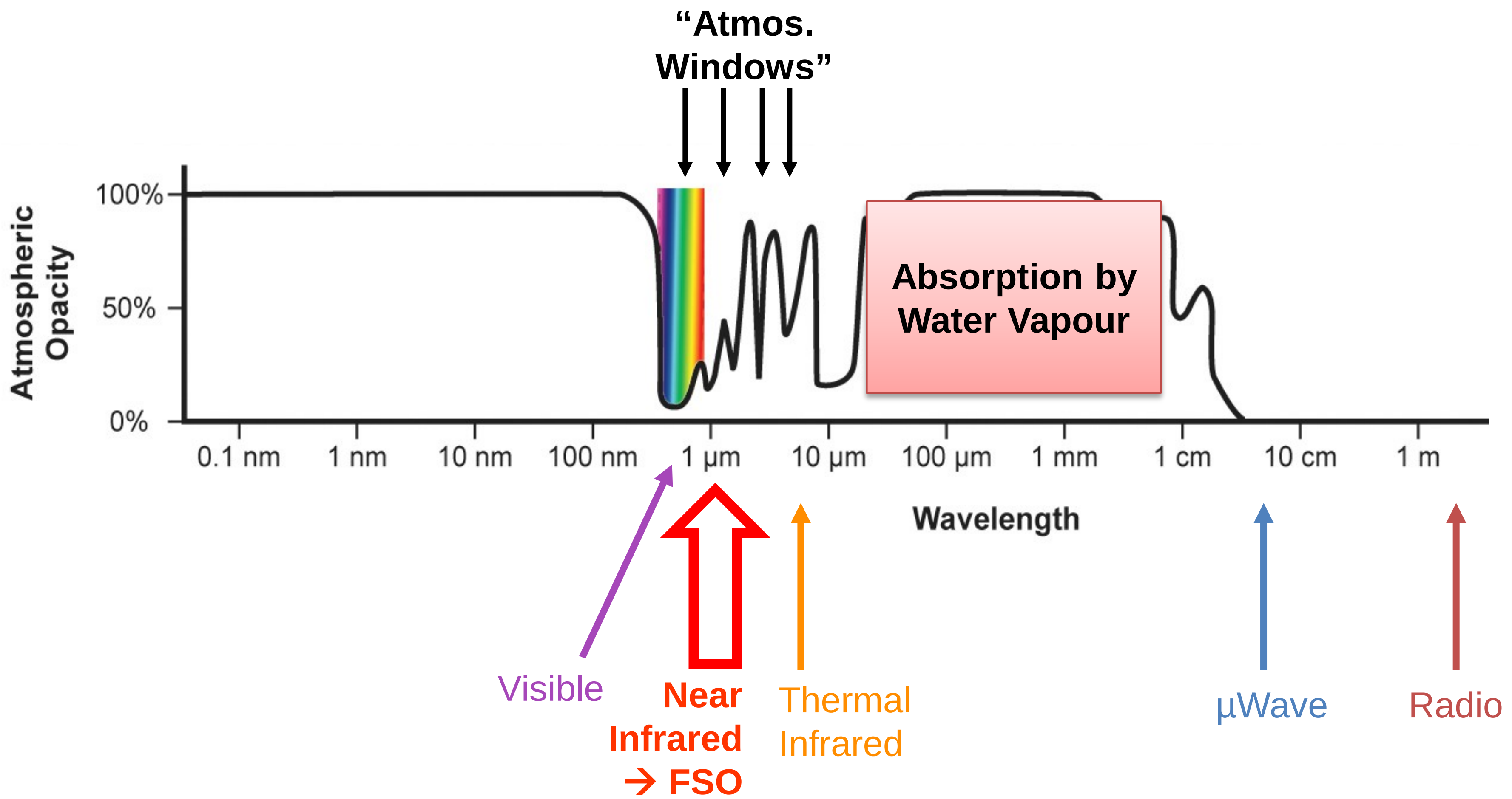
Relevant for optical propagation



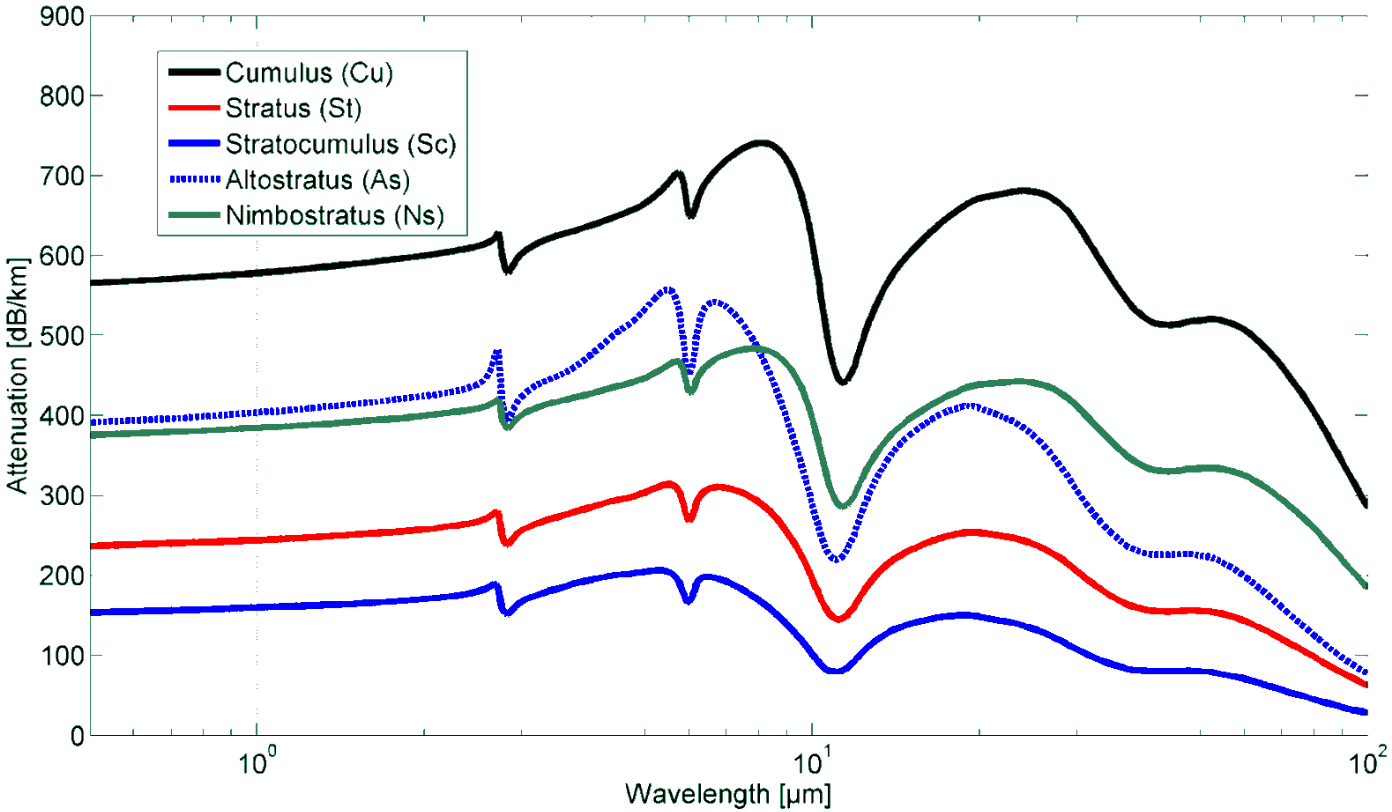
Atmospheric Effects on Optical Signals



Atmospheric Molecular Absorption

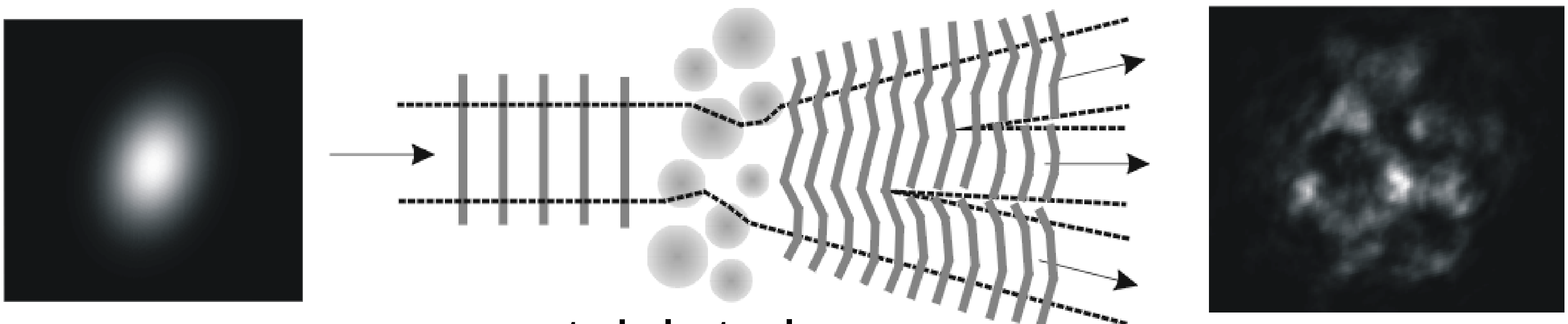


Mie-Scattering → Cloud attenuation
(up to several 100dB/km)



What happens when a laser beam passes through turbulent air?

Wavefront distortion → Interference



collimated laser beam at Tx

turbulent volume with IRT-strength „C_n^2“

Far-field intensity-speckles

Atmospheric Effects on Optical Signals

Attenuation

Index-of-Refraction-Turbulence (IRT)

- Intensity-Scintillations
- Wavefront-Distortions
- Beam-Broadening
- Beam Tilt → Beam Wander
- Rx Angle-of-Arrival Fluctuations

Strengths of effects is scenario-dependent
(beam-divergence, wavelength, distance, C_n^2-profile)

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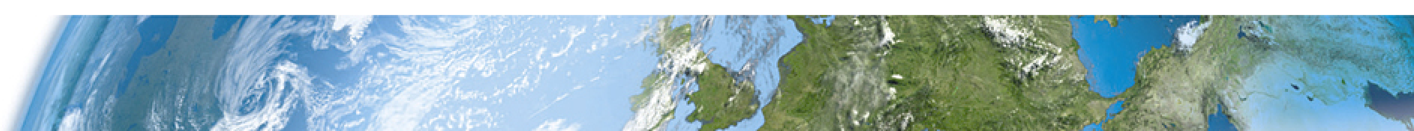
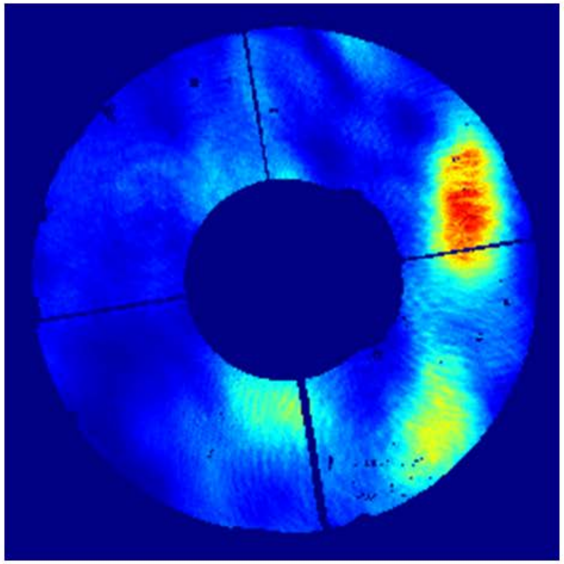


Examples of Intensitiy Scintillation Patterns at Receiver Telescope

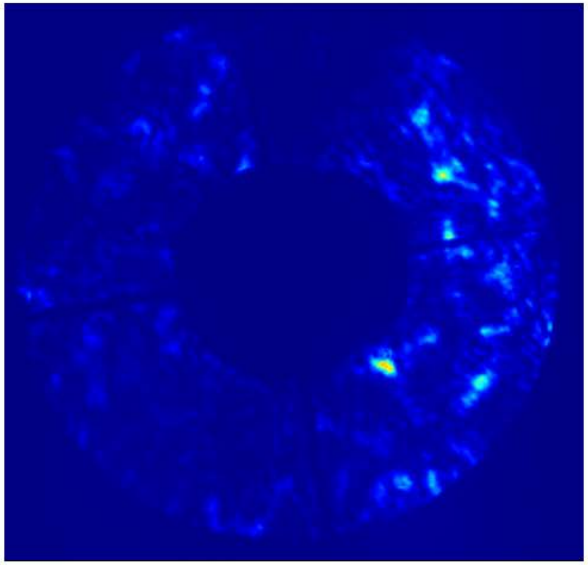
Scintillation Pattern Structures < $D_{Rx\text{-}Antenna}$

Low turbulence, large speckles:



(satellite downlink at high elevation)

Strong turbulence, small speckles:

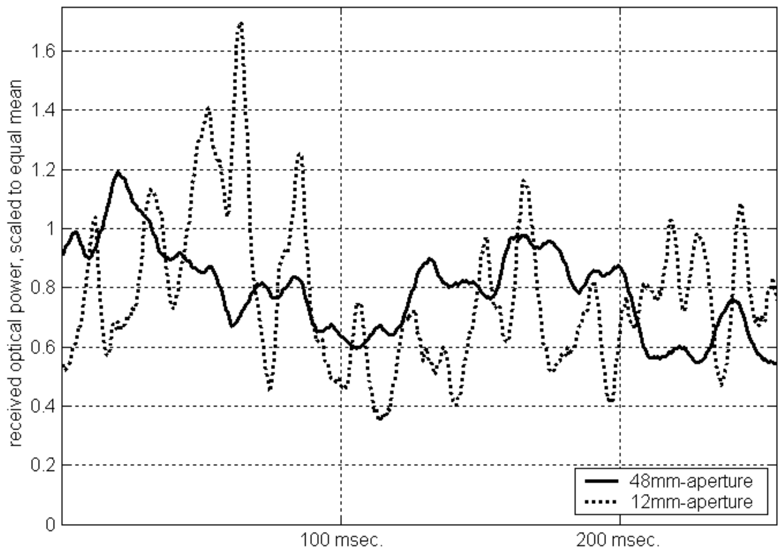


(long horizontal path)

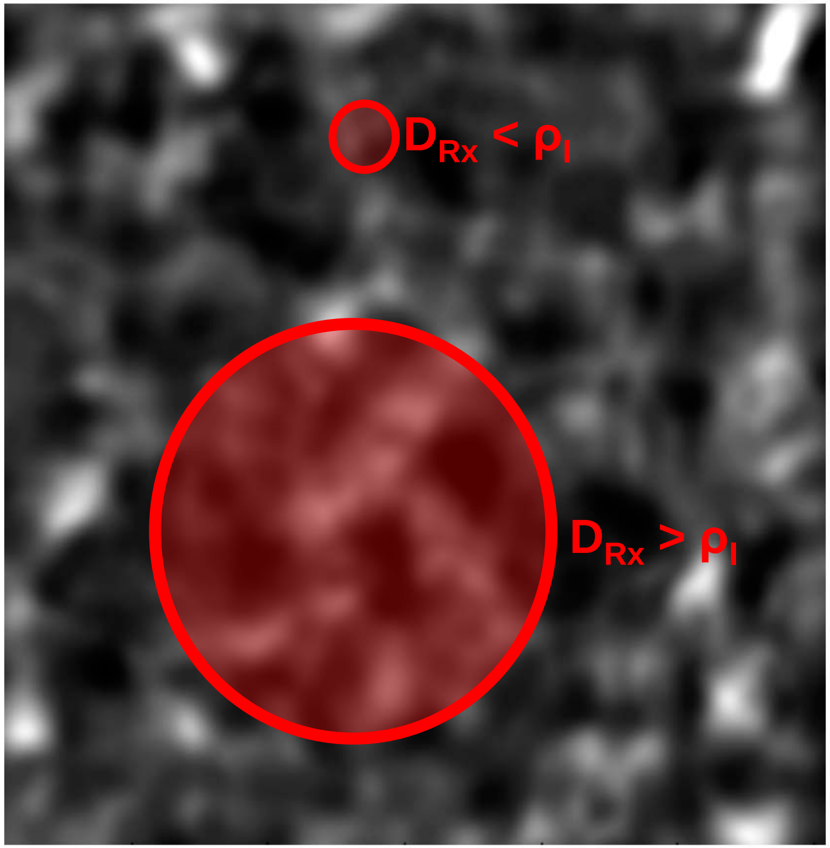
$D_{Rx\text{-}Telescope} = 1m$

Downlink: Rx-Power - Aperture Averaging Effect

$$P_{Rx}(t) = \int_{A_{Rx}} I(\vec{r},t)\,dA$$



Larger Rx-Aperture reduces variance of P_{Rx} in magnitude and spectrum



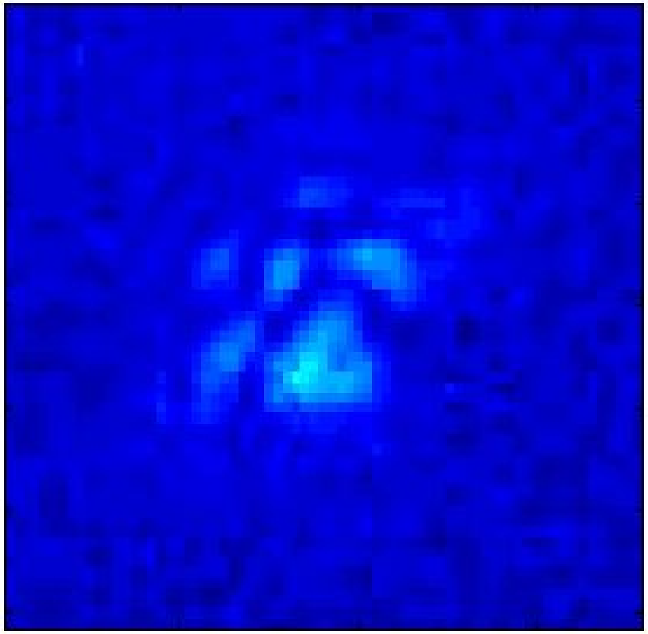
Intensity Distribution at Receiver (Far-Field Speckle Pattern)

Downlink: Wavefront-Distortions - Adaptive Optics

… to enable Single-Mode Fiber-Coupling, or Heterodyning with LO

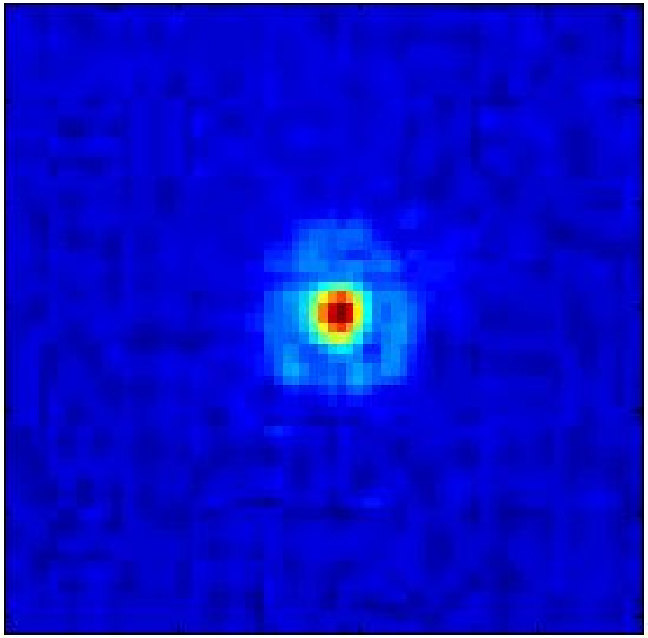
… requires correction of atmospheric phase-errors in realtime

Adaptive Optics not activated



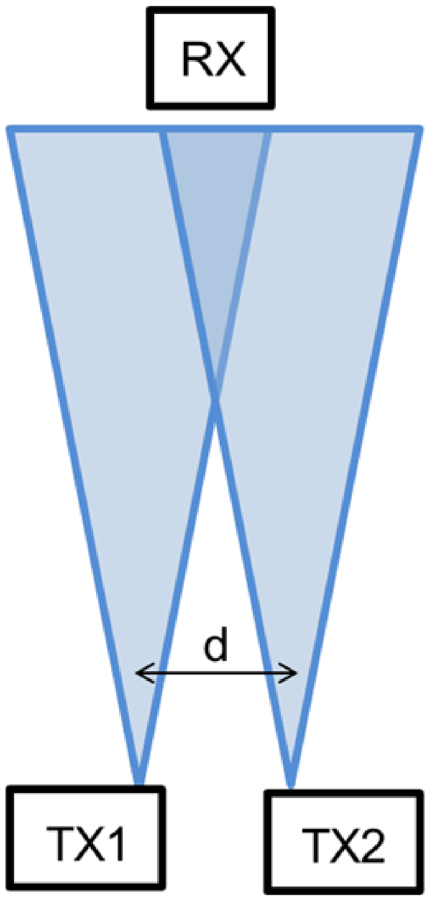
Focal Intensity Speckles prevent efficient fiber-coupling or heterodyning with LO

Adaptive Optics activated

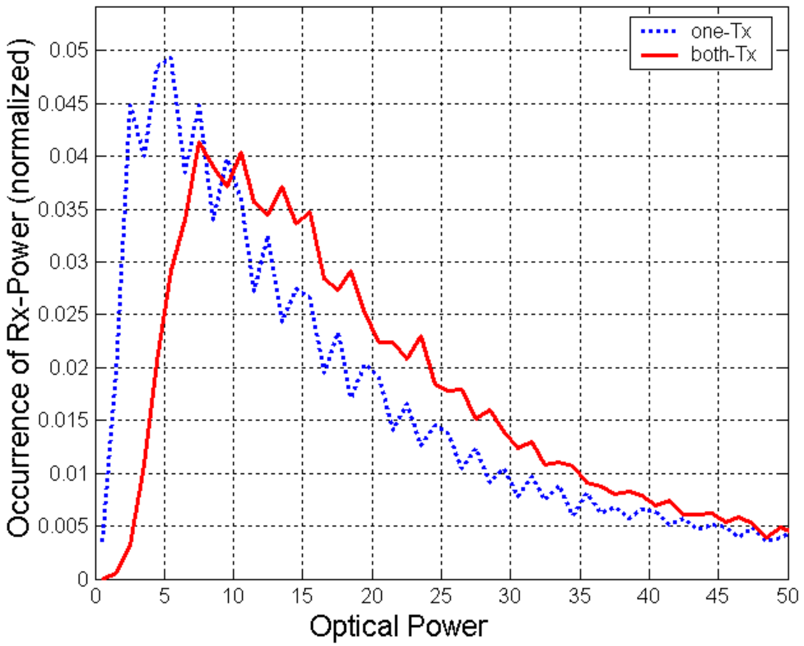


Corrected Phase allows near-ideal focal spot

Uplink: Transmitter Diversity

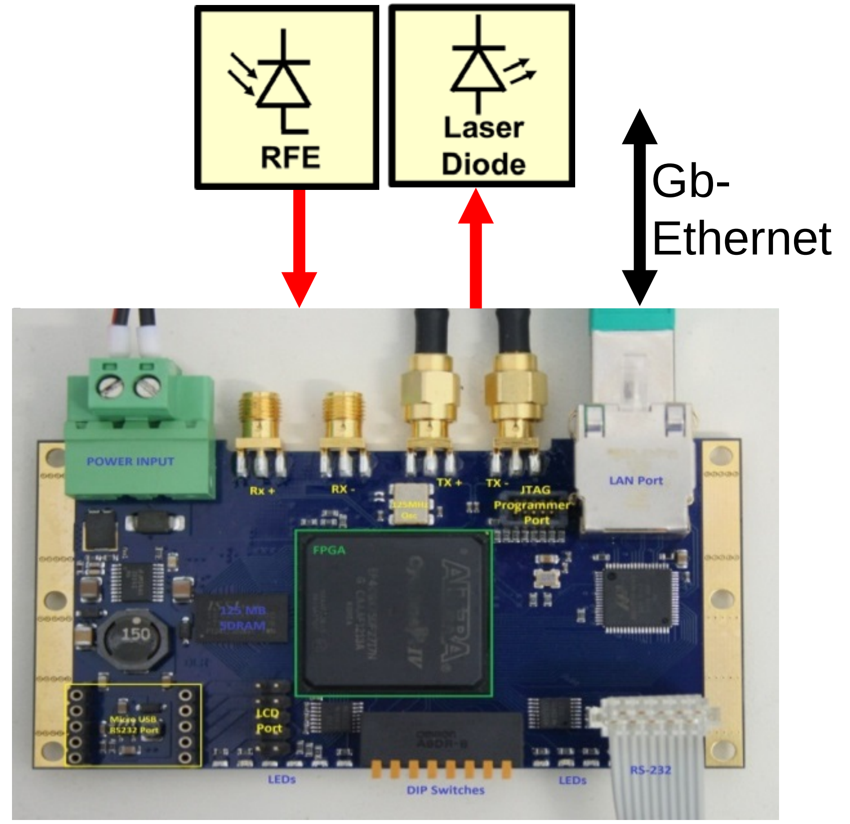


- Several Transmitters each generate independent speckle patterns,
- Superpositioned at the Rx, these smooth out fades and surges



Down- & Uplink: Error Control Coding

- Delay-Tolerant Transmission Management (only non-realtime scenarios)
- Low-overhead ARQ for lossy return channel
- Interleaved Packet-Layer FEC (Burst Errors from IRT-Fading, 1..10ms)
- Robust Data-Recovery and Bit-Level FEC



FPGA-Implementation of Laser-Ethernet-Transceiver (LET)

- Introduction to FSO in Space Applications
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- **Optical GEO Feeder-Links**
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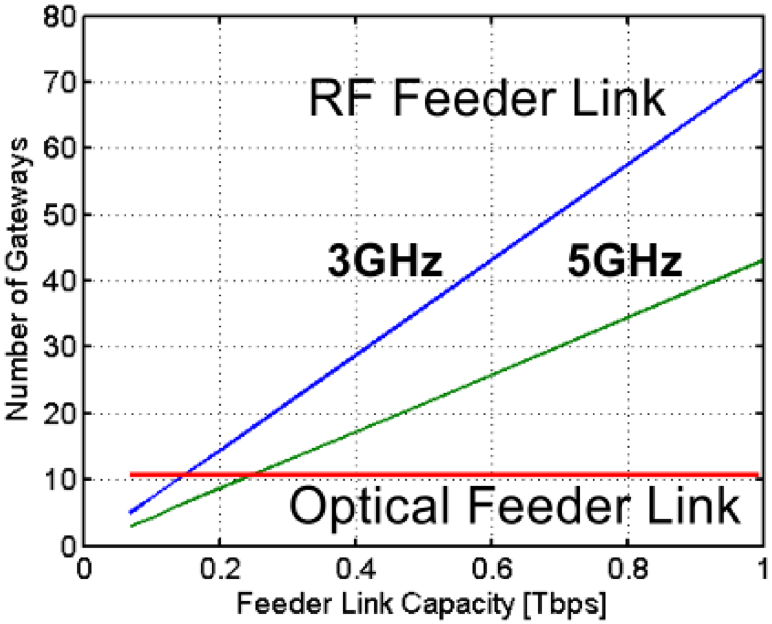
Motivation for Optical GEO Feeder Links in future Com. Satellite Systems

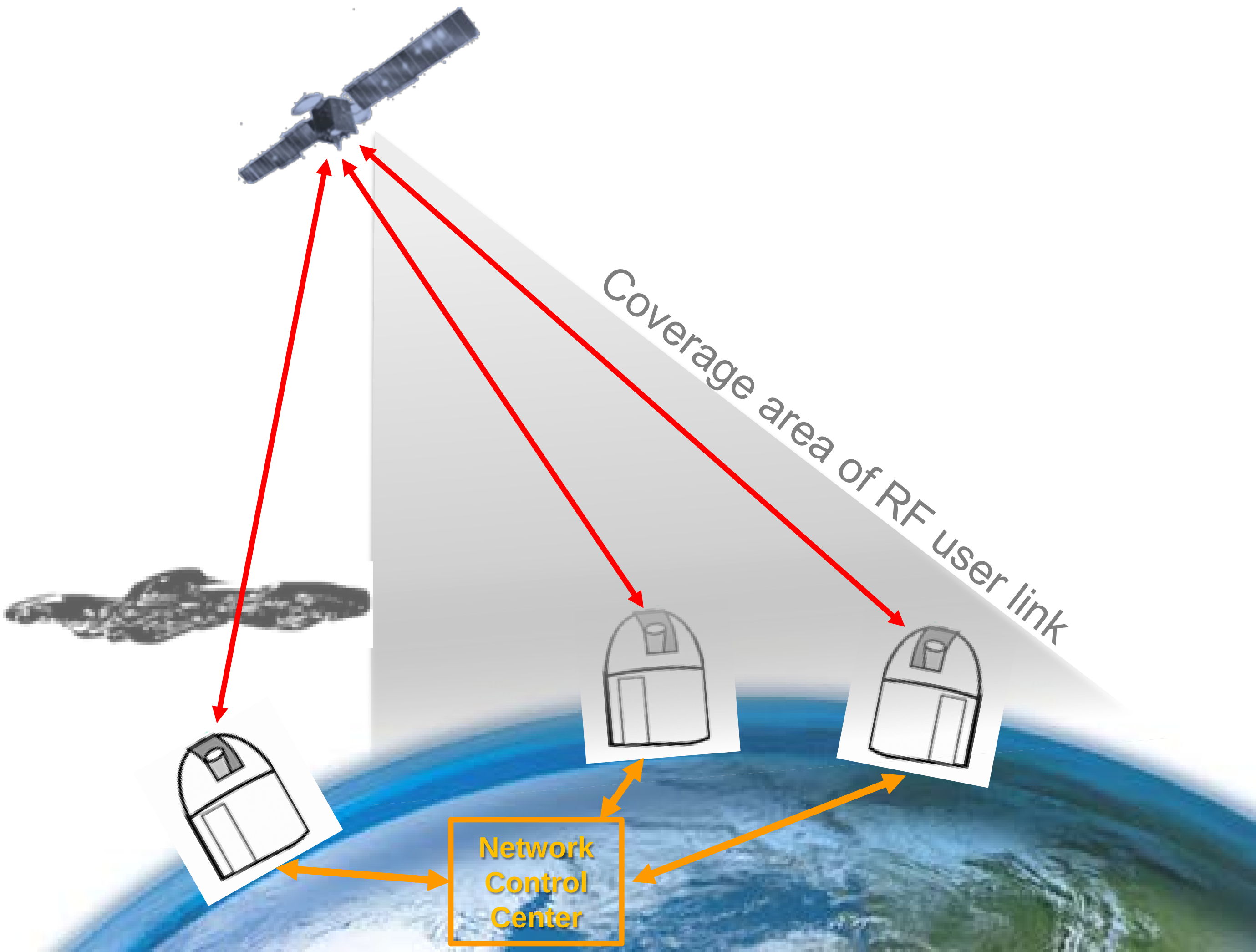
- Terabit-per-second SatComm is required in future (Europ. Digital Agenda)
- Number of required **RF ground stations** grows linear with throughput
- Optical Feeder Links provide >1Tbps over one **optical ground station**

- Number of OGSs in the network is driven by robustness against cloud blockage

→ „**at least one OGS must be available**"



Optical Ground Station Diversity for Mitigation of Cloud Blockage



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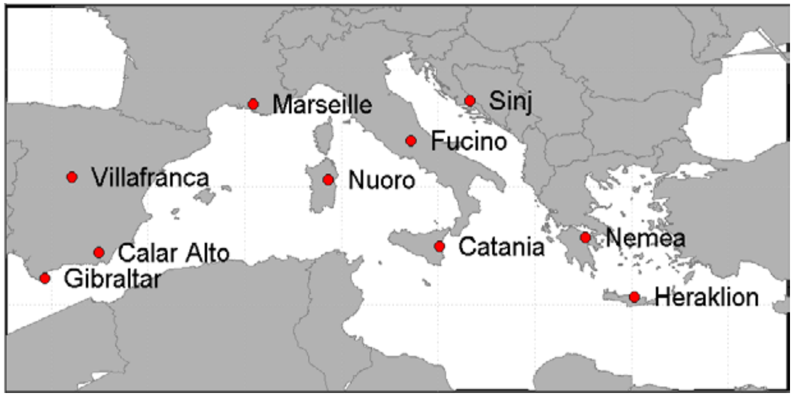
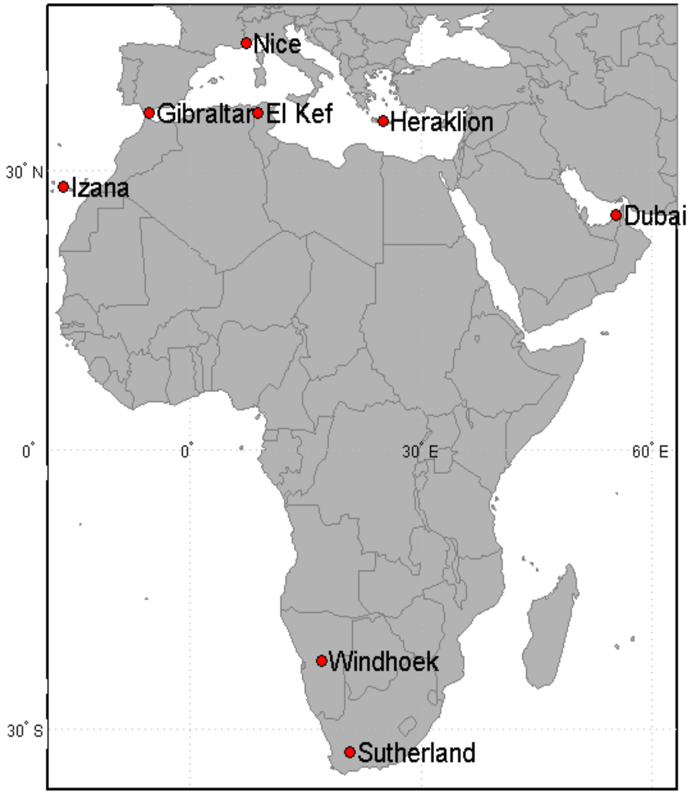
Cloud-Blockage Mitigation – OGS-Network Availability

11 European stations
Availability = 99.67 %

10 Mediterr. stations
Availability = 99.89 %



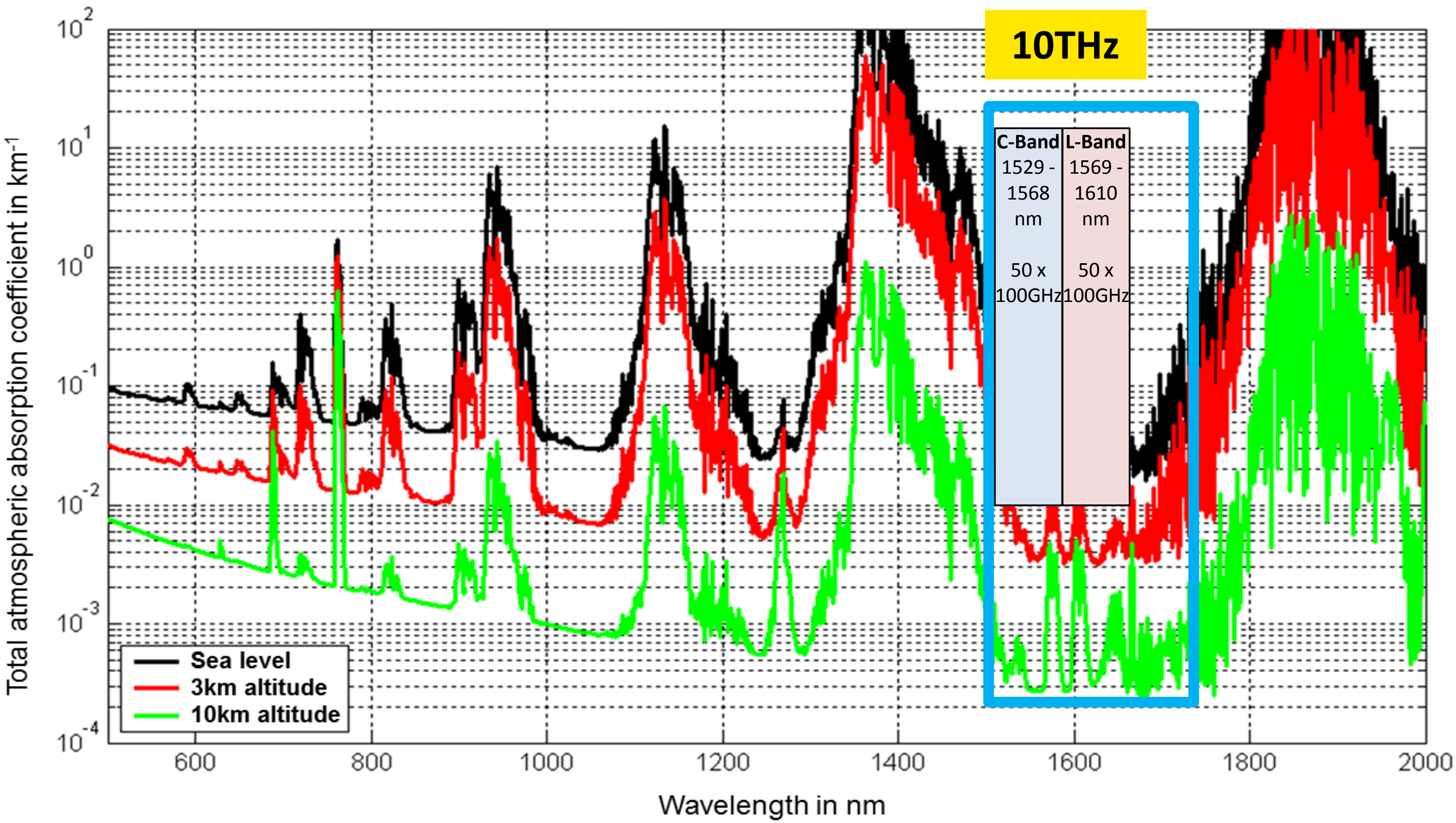


8 stations Inter-Continental
Availability = 99.971 %

Data-basis: Satellite images and simultaneous ground observations (from 1990 to 2006)

Available Optical Spectrum based on DWDM-Technology

(Dense Wavelength-Division Multiplexing)



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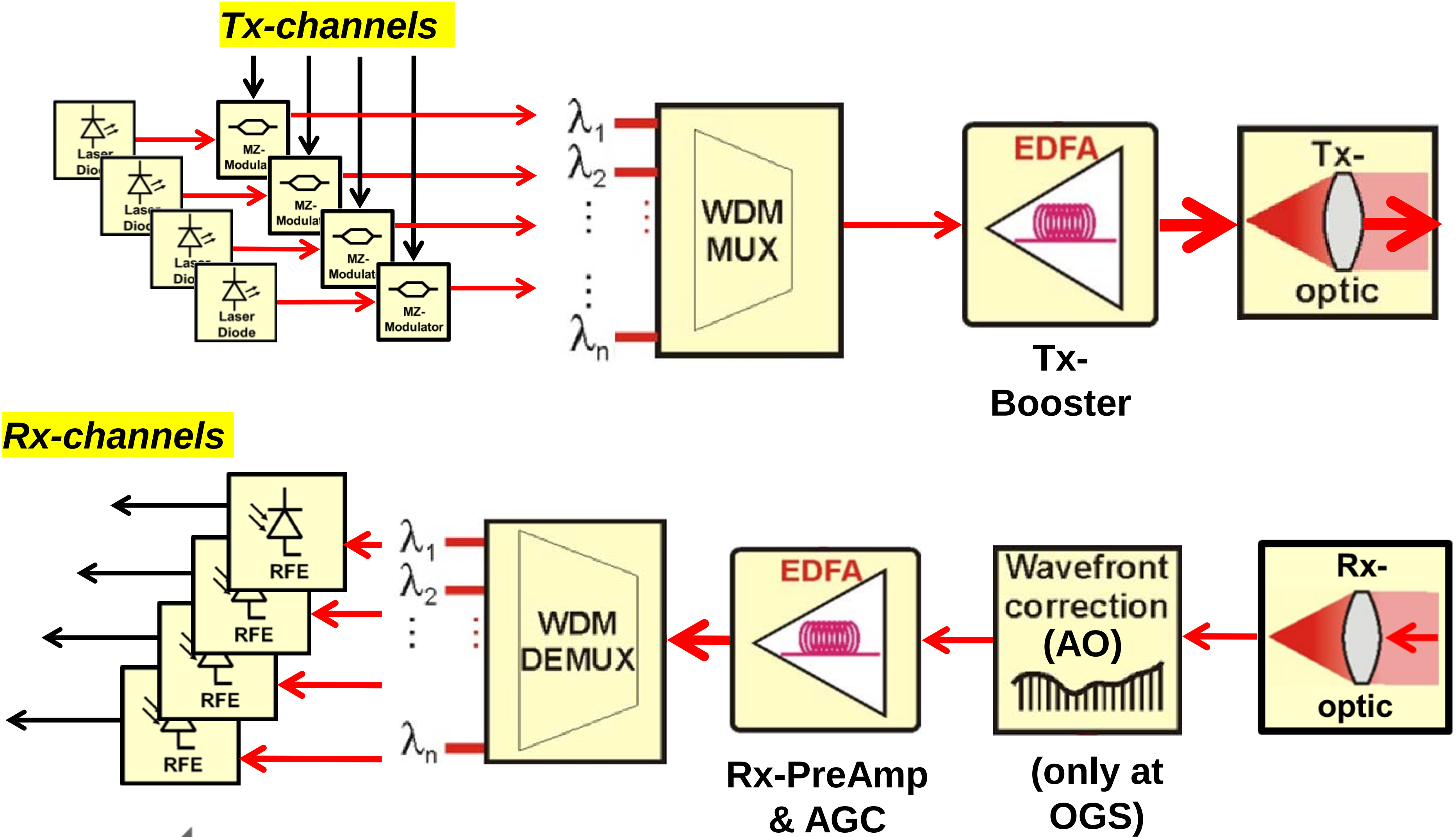
DWDM-System for Optical GEO Feeder-Links



OGEOFL: Implications of the Uplink Channel

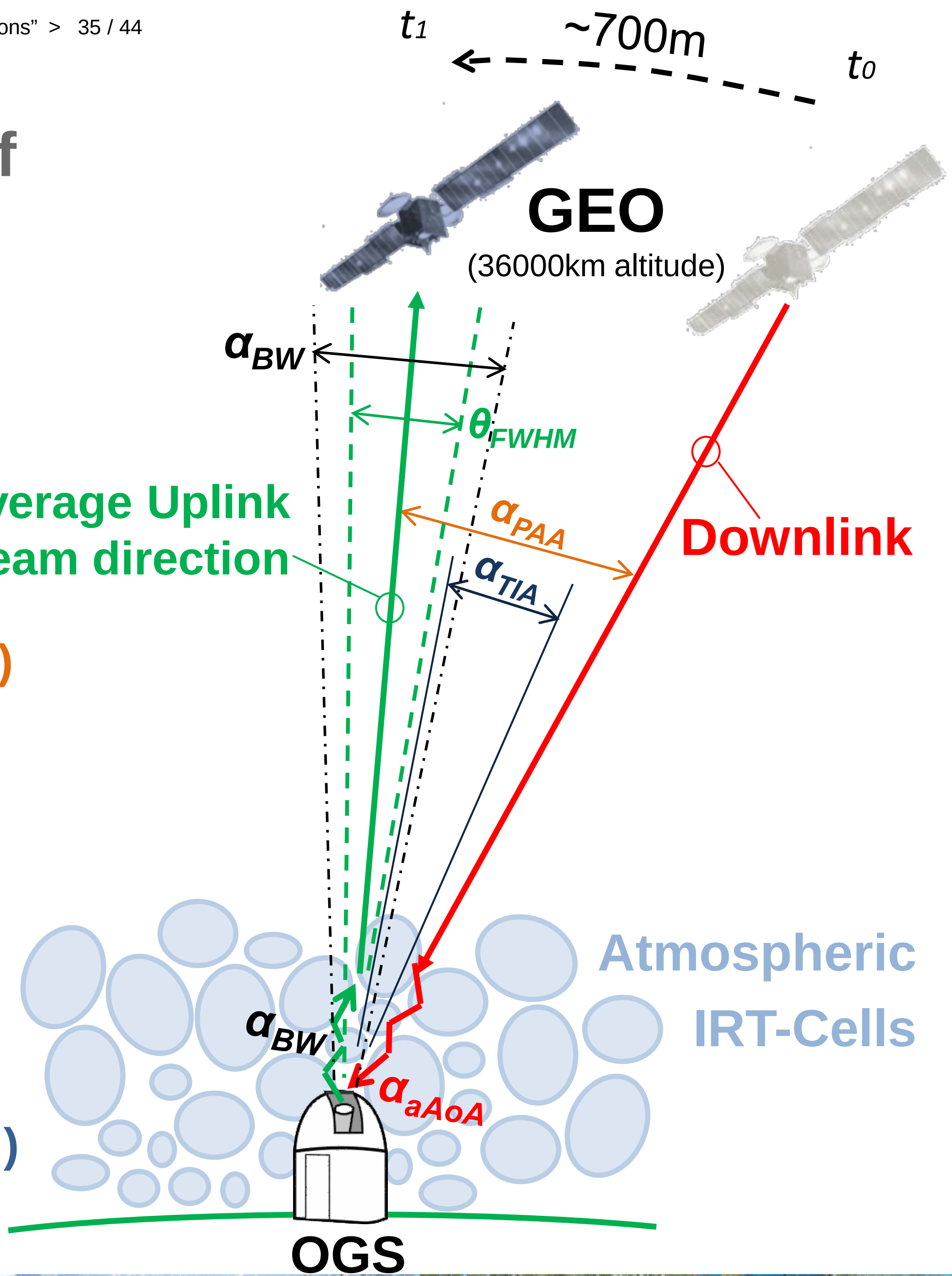
α_{aAoA}: Downlink atmos. Angle-of-Arrival

α_{PAA}: Point-Ahead Angle (~18μrad)

θ_{FWHM}: effective uplink divergence angle (~10μrad)

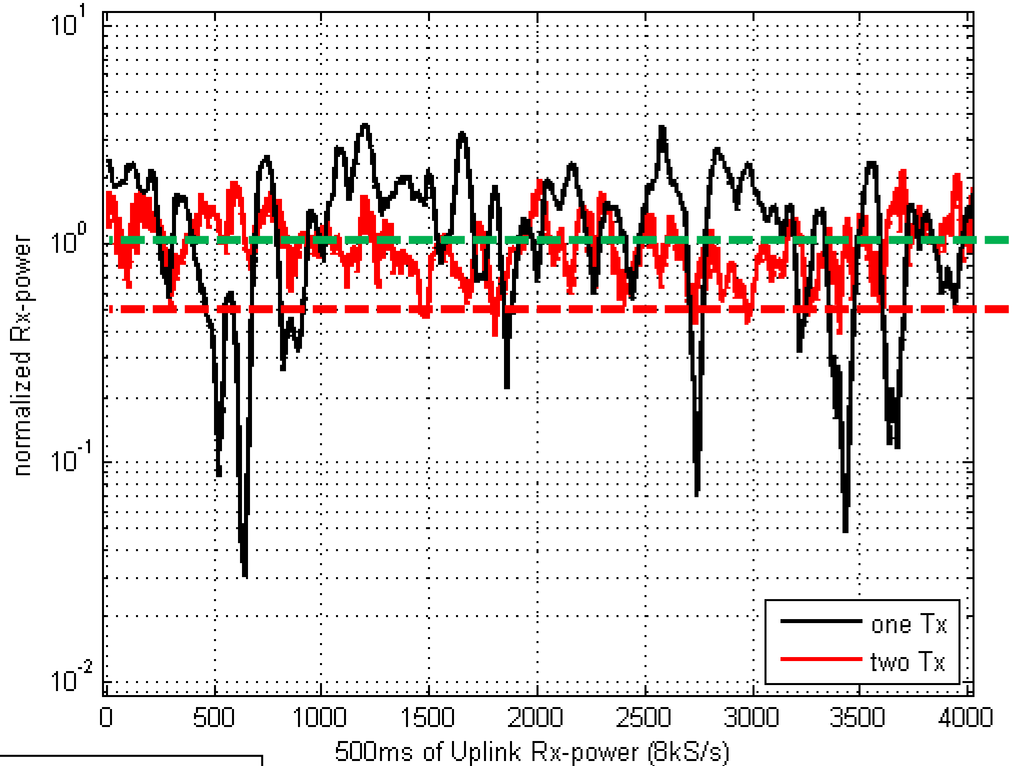
α_{BW}: Uplink atmos. Beam-Wander (~10μrad)

α_{TIA}: Tilt-Isoplanatic Angle (dep. on elevation, altitude, …)



Measured *Uplink* Received Power at GEO: Miss-Pointing and Tx-Diversity

Rx-Power with second Tx-Beam



average

-3dB fade threshold

Alternative Solution:
Probing with Laser Guide Star

Source: „ArtemEx-Project“, 820nm Uplink to GEO „Artemis“, from ESA-OGS at Izania, Tenerife

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Options for Transmission Formats in OGEO-FL

Analog Transparent / Radio-over-FSO:

- Analog modulated Laser (Intensity or complex Field)
- Requires physical equalization and AGC-Techniques
- one DWDM-ch. per Ka-Band Spotbeam → inefficient

Digital Transparent:

- Transmitting digitized Samples over the optical FL
- DAC & ADC at GEO
- Possibly with additional opt. FEC
- More flexibility, better spectrum-efficiency

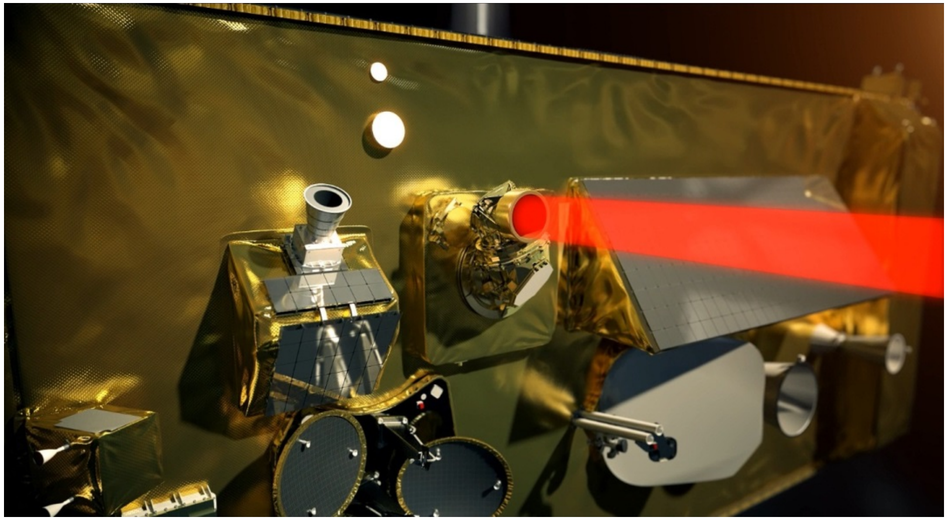
Fully Regenerative:

- Complete FEC- and DVB De-/Encoding on GEO
- Highest efficiency
- High processing power required

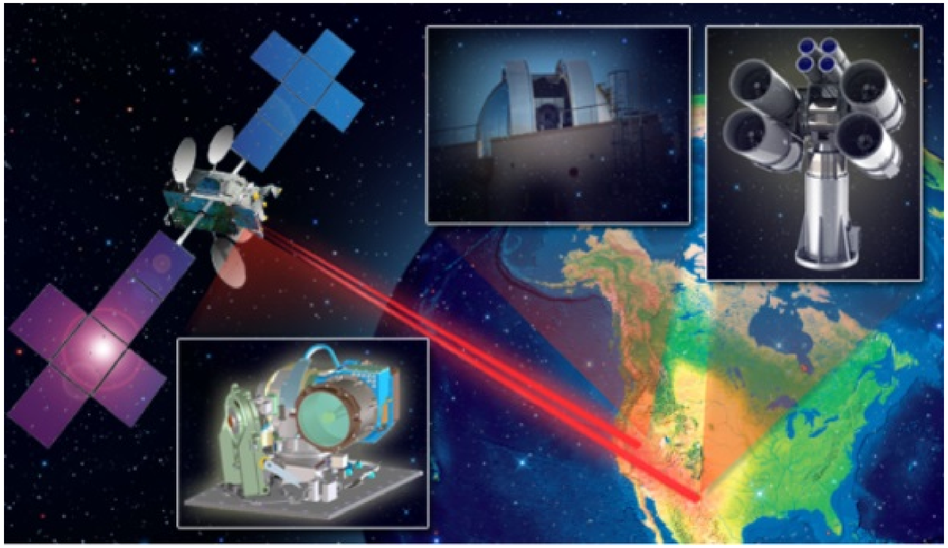
→ **Increasing Complexity and Efficiency**

Precursor-Missions on Optical GEO Feeder Links

LCT on ALPHASAT (-EDRS)
- test a coherent space-ground link, 1 GEO Terminal (launched 2013)



LCRD: GND-GEO-GND with DPSK and fading-tolerant Modem, 2 GEO Terminals (planned 2017)



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Pictures: ESA, NASA

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Summary and Outlook

- Optical Data-Relay System „EDRS“ for LEO→GEO implemented
- Laser Links for Exploration-Missions have been demonstrated
- Several LEO-Downlink Demonstrations
- Optical GEO Feeder Link Technology is beeing developed

European Studies on Optical GEO Feeder Links
(selection)

- **RIVOLI**
  (trade-off study on transmission formats for OGEOFL; ESA)
- **ONUBLA**
  (OGS Cloud Availability and System Throughput; ESA)
- **BATS**
  (general on advanced throughput Comms-Sat Systems
  incl. OGEOFL and transmission format options; FP7)
- …

Standardization Activities

- CCSDS (Consultative Committee for Space Data Systems):
  SLS-OPT Optical Communications Working Group:
  - Blue Book for Optical Communications Physical Layer
  - Blue Book for Optical Communications Coding & Synchronization
  - Green Book for Optical Communications Concepts and Terminologies
  - Green Book for Real-Time Weather and Atmospheric Characterization Data

- ITU (International Telecommunication Union):
  - RECOMMENDATION ITU-R 1621 / 1622, "Propagation data / Prediction methods required for the design of Earth-space systems operating between 20 THz and 375 THz," 2005

Further Reading

Papers (selection):

- S. Dimitrov, B. Matuz, G. Liva, R. Barrios, R. Mata-Calvo, D. Giggenbach, "Digital Modulation and Coding for Satellite Optical Feeder Links", ASMS 2014, Livorno, Italy, Sept. 2014
- W. Cowley, D. Giggenbach, R. Mata Calvo, "Optical Transmission Schemes for GEO Feeder Links", IEEE ICC 2014 - Selected Areas in Communications Symposium, Sydney, June 2014
- Mata-Calvo, Becker, Giggenbach, Moll, Schwarzer, Hinz, Sodnik, "Transmitter diversity verification on ARTEMIS geostationary satellite", SPIE Photonics West, Feb. 2014
- D. Giggenbach, R. Barrios, F. Moll, R. Mata-Calvo, S. Bobrovskyi, F. Huber, N. F.D. Johnson-Amin, F. Heine, M. Gregory, "EFAL: EDRS Feeder Link from Antarctic Latitudes - Preliminary Results of Site Investigations, Availability, and System Requirements" ICOSOS2014 - International Conference on Space Optical System s and Applications, Kobe, Japan, May 2014
- D. Giggenbach, "Optical Satellite Feeder Links for Terabps Throughput." DLR Institute of Communications and Navigation, Presentation, on elib.dlr.de

Text Books (selection):

- W.K. Pratt, "Laser Communications Systems", John Wiley & Sons, 1969
- R.M. Gagliardi, S. Karp, „Optical Communications", John Wiley & Sons, 1976
- S.G. Lambert, W.L. Casey, "Laser Communications in Space", Artech House, 1995
- L.C. Andrews, R.L Phillips, " Laser beam propagation through random media", SPIE-Press 2005


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"Optical Free Space Links for Satellite-Ground Communications"

by Dr. Dirk Giggenbach, for ASMS/SPSC-2014 in Livorno

Abstract:

Due to the ever increasing data-throughput together with limited RF-spectrum, new transmission technologies at smaller carrier wavelengths are being developed for use in space-missions. Optical Space-Ground links are currently evaluated, developed, and tested in all relevant point-to-point link scenarios, namely EO-LEO downlinks, GEO feeder links, as well as for space-probe telemetry. Some of these scenarios are currently being demonstrated by precursor missions. While solving the datarate-bottleneck, however, new challenges need to be considered, these being the influence of the atmosphere on the signal propagation, as well as the challenging pointing and tracking requirements.

This tutorial introduces the scenarios and available optical free-space transmission technologies, and goes more into detail on the influence of atmospheric index-of-refraction turbulence and atmospheric attenuation on the signal propagation. An overview of ongoing and planned technology demonstration missions is given.

length of this tutorial: 1h + 15min